A High-Fidelity Headphone System for Simultaneous EEG/fMRI Experiments

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Introduction. In this abstract we describe an electrostatic MRI-compatible headphone system with passive sound-attenuation and electrical shielding that eliminates noise coupling with EEG. Measurement of electroencephalogram during functional MRI is an important emerging technique for functional neuroimaging studies that can improve spatiotemporal resolution [1] and reveal temporal covariance between EEG and fMRI [2]. One important class of EEG/fMRI experiments involves estimating event-related potentials (ERPs) from sensory or cognitive stimuli during simultaneous fMRI. Auditory ERP experiments are best observed using stimuli with high bandwidth, such as click trains or noise bursts, and are typically presented using headphones whose frequency response extends to 15 or 20 kHz. Functional MRI studies pose the additional complication of acoustic scanner noise, which necessitates hearing protection, and MRI-compatibility, which rules out standard magnetic-coil headphones. Commercially-available solutions for fMRI studies use either air-tube sound transmission with sound-attenuating earmuffs (e.g., Avotec, Inc., Stuart, FL, USA), giving a frequency response of 4 to 6 kHz, or electrostatic sound elements without hearing protection (Koss Corp., Milwaukee, WI, USA), with a frequency response in excess of 20 kHz. Unfortunately, electrostatic headphones emit electromagnetic fields that couple to EEG recordings with an amplitude that is orders of magnitude higher than the EEG signal itself (FIG 1, solid line). The headphone system described in this abstract allows for observation of auditory steady-state responses (ASSRs) approximately 1 micro-volt in amplitude.

Methods. The electrostatic headphone elements were removed from a set of Koss ESP-950 headphones, electrically shielded, and placed within a set of sound-attenuating earmuffs (Silenta Ergomax, Oy Silenta Ltd., Finland). Electrical shielding was accomplished by replacing the first 6 feet of headphone cable with shielded computer cabling, and by placing a conductive fabric sock constructed from silver-coated sheer nylon (www.lessemf.com, Cat. #A209) over the headphone element. The conductive fabric was chosen for its low resistivity (<5 Ohms/square) and low acoustic absorption. Shielded cabling was limited to 6 feet to reduce capacitive load on the electrostatic amplifier system (<600 pF). The cable shield was connected to the conductive sock using a combination of indium solder and copper foil tape, and terminated on a copper mesh housing encasing the Koss amplifier unit via a single wire running along the remaining length of the headphone cable. The conductive sock was electrically insulated from the headphone using a thin plastic membrane. The amplifier unit was powered from a 9.6V rechargeable battery (placed outside the MRI room and routed through penetration panel), to reduce the risk of electrical shock. The battery ground terminal and amplifier shield were connected at the penetration panel.

Sound stimuli consisted of noise-bursts (12.5 msec) and click-trains (1 msec) presented at 25 msec intervals, 30 seconds ON, 30 seconds OFF, using a laptop running Presentation 0.76 (Neurobehavioral Systems, Albany, CA), driving an Echo Indigo 24-bit sound card (Echo Digital Audio, Carpinteria, CA, USA). Acoustic attenuation recordings were made using an electret condenser mic (SM-93, Shure, Niles, IL) by comparing scanner noise during functional scanning (Siemens Trio) with the microphone placed inside and then directly outside the headphone earmuff, for both Avotec and shielded-electrostatic systems placed on a human volunteer. Electromagnetic noise coupling measurements were made by coating an MRI phantom in EEG paste (Elefix, Nihon Kohden, Japan), placing adjacent bipolar pairs of EEG electrodes in the coronal plane to simulate the M1/2, T7/8, C3/4, C1/2, and Cz positions, fixing the headphone earpieces over the phantom, and recording using an in-house 24-bit EEG/fMRI recording system sampling at 1 kHz. Recordings were made with the headphone shield disconnected and floating ("unshielded") and then with the shield connected ("shielded"). Auditory ERPs and ASSRs were recorded from 24 human volunteers (similar stimuli and EEG setup) using the shielded-electrostatic headphone system. All studies were conducted with the approval of the Human Studies Committee at MGH, with informed consent from all volunteers.

Attenuation and noise coupling were studied by computing multi-taper power spectral estimates [3] for each condition, and taking ratios of the appropriate power spectra to determine attenuation or noise coupling:

Acoustic Attenuation = P(Inside Earmuff)/P(Outside Earmuff); Electromagnetic Noise Coupling = P(Stim. ON)/P(Stim. OFF).

Results and Discussion. Acoustic attenuation for the shielded-electrostatic and Avotec systems were similar, 32.8 and 38.1 dB, respectively, averaged between 0.8 and 20 kHz. FIG 1 shows the frequency response of the electromagnetic noise coupling, on a dB scale, for the unshielded (solid) and shielded (dotted) cases, illustrating that the shielding reduces electromagnetic noise coupling by over 40dB throughout the bandwidth of the EEG recording device. To quantify the shielding effectiveness with greater sensitivity, FIG 2 compares the shielded noise coupling (Phantom) with the 40-Hz ASSR from a human volunteer on a linear scale (perfect shielding corresponds to P(Stim. ON)/P(Stim. OFF) = 1), illustrating that the shielded noise coupling is indistinguishable from background noise and is well below the level of the measured electrophysiological response (approx 1 uV p-p). For the human studies, there were no discernable image artifacts during MRI due to the headphones.

Conclusions. We have constructed a high-fidelity headphone system based on electrostatic technology with passive acoustic noise attenuation in excess of 30 dB that is compatible with simultaneous recording of ERPs, EEG, and fMRI. This system has been validated with both phantom studies and human studies (N=24), and the design can be applied to other electrophysiological techniques such as intracranial or multi-unit recordings.

References. [1] Liu, et al. Hum.Brain Mapp. 16 (1):47-62; [2] Goldman RI, et al. Neuroreport. 13(18):2487-92; [3] Percival and Walden, Spectral Analysis for Physical Applications, Cambridge University Press, 1993.